1980ApJ...240..779P

THE ASTROPHYSICAL JOURNAL, **240**:779–784, 1980 September 15
© 1980. The American Astronomical Society. All rights reserved. Printed in U.S.A.

INFRARED PHOTOMETRY OF THE SEMISTELLAR NUCLEUS OF M31

S. E. PERSSON,[1] J. G. COHEN,[2] K. SELLGREN,[3] J. MOULD,[1] AND JAY A. FROGEL[4]
Received 1980 February 25; accepted 1980 March 25

ABSTRACT

New broad-band infrared *JHK* data and narrow-band CO and H_2O indices for the semistellar nucleus of M31 are presented. The data were obtained specifically to test a prediction of a recent synthesis model by Faber and French in which the ratio of dwarf-to-giant light increases strongly in going from the bulge to the nucleus of M31. The new infrared data do not support such a model. Some alternative explanations for the behavior of the various indices are given, but the apparent conflict between the Faber-French interpretation of the strength of the Na I λ8190 feature and our data is not satisfactorily resolved.

Subject headings: galaxies: individual — galaxies: nuclei — galaxies: stellar content

I. INTRODUCTION

The purpose of this paper is to present and discuss new broad-band and narrow-band infrared photometry of the nuclear region of M31. We were motivated to make the observations by the recent results of Faber and French (1980, hereafter FF) who have constructed stellar population models for the nucleus and bulge of M31 on the basis of observations of the Na I λ8190 feature, together with other optical line strength data. Their best model of the nuclear region has a strongly dwarf-enriched nucleus embedded in a giant-dominated bulge. They make specific predictions for the values of several infrared colors and indices. A comparison of our new data with the predicted differences in the colors and indices between the nucleus and bulge provides a sensitive test of their model.

II. OBSERVATIONS AND RESULTS

Three different kinds of observations were made with the 5 m Hale telescope on Palomar Mountain and the 2.5 m Hooker telescope on Mount Wilson to measure the change in infrared colors and indices near the nucleus of M31. We shall henceforth call the inner 2″.5 diameter region the "nucleus."

a) Narrow-Band CO *and* H_2O *Indices*

In the first set of measurements the standard CO and H_2O indices in the 2 μm region, defined by Frogel *et al.* (1978) and Aaronson, Frogel, and Persson (1978), were obtained in 1″ to 1″.5 seeing with iris diaphragm apertures of diameter 2″.5, 10″, and 15″, carefully centered on the nucleus. A standard infrared photometer was used on the 5 m Hale telescope, and the signal beam/sky beam separation was 17″.5. The multi-aperture measurements were made completely differentially, i.e., large and small apertures were measured alternately, and the three individual filters required to measure the two narrow-band indices were alternated in the sequence 1-2-3-3-2-1 or 1-2-2-1-1-3-3-1. This technique should remove all linear changes in guiding, seeing, and transparency. Data were obtained on 3 nights; the individual differences were found to agree to within the statistical uncertainties on each night. We were interested only in the *differences* between the indices for the various apertures and took the actual values for the indices from previous unpublished data for a 10″ aperture.

A point of concern in detecting small radial differences in this multiaperture photometry is that the signals from the larger apertures not be dominated by the semistellar nucleus itself. This is in fact not a problem, as is shown by the relative fluxes at 2.2 μm (*K* filter) given in column (6) of Table 1; these data are discussed below. The flux scales approximately linearly with aperture size, so that ~80% of the signal within 13″.7 is from a region *outside* the 2″.5 nucleus.

No corrections to the CO or H_2O indices were made for flux in the photometer "reference" or "sky" beam, which was 17″.5 north and south of the signal beam. In all cases the flux in the reference beam was too small (less than ~25% of the signal from the nucleus) to significantly affect the differential colors. This is because the large aperture data (in Table 1 and discussed below) show no gradient in the narrow-band indices out to an aperture diameter of 107″; thus the indices of the bulge at the position of the reference beam are close to those of the nucleus itself, and no correction to the nuclear color is indicated.

A further potential source of systematic error is a variation of the system response at different places in the larger apertures. The 15″ aperture was mapped using a star in the three narrow-band filters used to

[1] Mount Wilson and Las Campanas Observatories, Carnegie Institution of Washington.

[2] Palomar Observatory, California Institute of Technology.

[3] California Institute of Technology.

[4] Cerro Tololo Inter-American Observatory, which is supported by the National Science Foundation under contract no. AST 78-27879.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

TABLE 1

INFRARED MEASUREMENTS OF THE NUCLEUS OF M31

Aperture Diameter (arc sec) (1)	CO (2)	H_2O (3)	J-H (4)	H-K (5)	K (6)	V-K (7)	$(V-K)_o$ (8)	Notes (9)
2.5	0.16 ± 0.01	0.14 ± 0.01	0.74 ± 0.03	. . .	9.11 ± 0.12	. . .	. . .	1
5.0	. . .	. . .	. . .	. . .	8.24 ± 0.07	. . .	. . .	1
10.0	0.15 ± 0.02	0.11 ± 0.02	. . .	. . .	7.36 ± 0.07	3.55	3.27	1
13.7	. . .	. . .	0.72 ± 0.03	0.26 ± 0.02	6.95 ± 0.06	3.42	3.14	2
15.0	0.15 ± 0.01	0.12 ± 0.03	0.74 ± 0.03	. . .	. . .	. . .	. . .	1
20.0	. . .	. . .	. . .	. . .	6.29 ± 0.05	3.49	3.21	1
27.4	0.175 ± 0.015	0.11 ± 0.02	0.70 ± 0.03	0.25 ± 0.02	5.81 ± 0.03	3.44	3.16	2
47.5	0.155 ± 0.015	. . .	0.73 ± 0.03	0.24 ± 0.02	4.83 ± 0.06	3.55	3.27	2
53.3	0.165 ± 0.015	0.11 ± 0.02	0.71 ± 0.03	0.24 ± 0.02	4.71 ± 0.03	3.46	3.18	2
107.1	0.155 ± 0.015	0.11 ± 0.02	0.72 ± 0.03	0.24 ± 0.02	3.72 ± 0.03	3.37	3.09	2
FF model 2" x 4" nucleus	≥0.125	≥0.185	. . .	. . .	. . .	. . .	3.74	3
FF model bulge	≥0.167	≥0.153	. . .	. . .	. . .	. . .	3.45	4

[1] This paper.
[2] Aaronson (1977). J-H and H-K data transformed from Aaronson's system to the present one [Δ(J-H) = 0.06, ΔH-K = 0.02]
[3] (Frogel et al. 1978).
Faber and French (1979) model colors for semi-stellar nucleus.
[4] Faber and French (1979) model colors for bulge light.

Note: The data in columns (2) through (7) have not been corrected for reddening. The $(V-K)_o$ values have been corrected; see text.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1980ApJ...240..779P

measure the CO and H_2O indices. The color indices were the same (± 0.01 mag) at all points in the aperture; thus this particular source or error is not important.

Table 1 lists the results of the multiaperture CO and H_2O measurements; the indices have *not* been corrected for reddening. The main result of these measurements is that the CO and H_2O indices increase by not more than 0.01 ± 0.01 mag and 0.02 ± 0.01 mag, respectively, going inward from the bulge to the nucleus of M31, where the bulge and nuclear values are characterized by the observations through the 15″ and 2″.5 diameter apertures. Table 1 also lists the data of Aaronson (1977); his data are on the same photometric system as the data presented here. Considering the available measurements of the nuclear region of M31, we conclude that there is no evidence for any systematic change in either the CO index or the H_2O index exceeding 0.01 mag and 0.02 mag, respectively, over the inner 100″.

On 1 night broad-band $J - H$ data were obtained for the 2″.5 and 15″ apertures. The $J - H$ color data are also listed in Table 1. Again, the 15″ aperture was mapped and convolved with an appropriate intensity distribution to yield "beam profile" corrections to the raw $J - H$ colors.

b) *The r − H Color near the M*31 *Nucleus*

In the second type of observation, the 5 m telescope was used to make simultaneous measurements, in 1″ seeing, of the $r - H$ color on an east-west line through the nucleus, in a 2″.5 diameter aperture. It was not practical to use a V filter, and instead an r filter of the Thuan and Gunn (1976) system was used ($\lambda_0 \approx 6500$ Å, $\Delta\lambda \approx 1000$ Å) with an S20 phototube. The 1.65 μm (H) infrared signal was split off with an infrared/visual dichroic filter, and the flux at r was measured through the dichroic. The reference beam locations were again 17″.5 north and south of the nucleus, for both the r and H fluxes. The correction to the $r - H$ *color* for flux in the reference beam is surely negligible, as the reference beam flux at each wavelength is only ~15% of the nuclear flux; and as was the case for the narrow-band corrections, the bulge color shows no large variations over the region sampled by the two beams (see below).

In this type of measurement one wants to measure the color through two identical, perfectly aligned, apertures. Drift scans across a star close to M31 showed that the r and H beam profiles were quite similar, and thus not only the relative colors on and off the nucleus, but also the absolute colors, are meaningful. The two apertures were, however, misaligned east-west by 0″.5, and it was necessary to shift the separate intensity profiles by this amount. Figure 1 shows the point-by-point instrumental magnitudes, shifted by 0″.5, relative to those measured on the nucleus itself. The data in Figure 1 are those obtained on the better of 2 nights; the data agree well between the 2 nights.

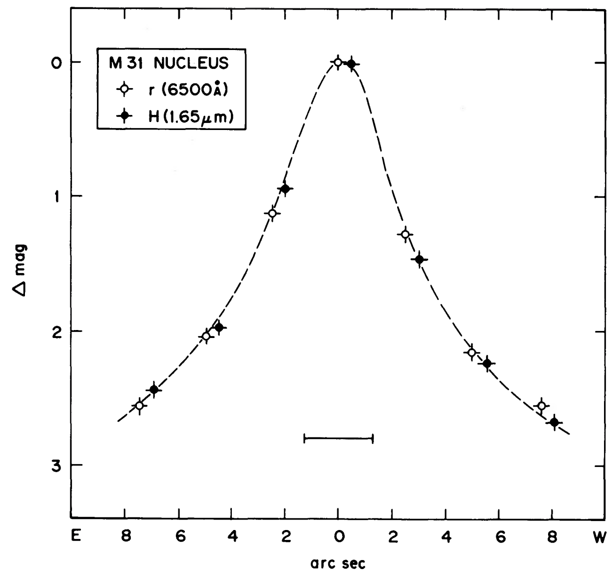

FIG. 1.—Relative instrumental magnitudes at r and H near the nucleus of M31. The error bars are $\pm 1\ \sigma_m$. The H data have been shifted by 0″.5 as discussed in the text. The dashed line is an eye fit to both data sets. The horizontal bar shows the aperture diameter at both r and H used in the observations.

The centering on the nucleus was done by maximizing the r signal, and this is borne out by the symmetry of the profile in r. Because of the 0″.5 offset between the separate r and H apertures, the infrared aperture was not exactly centered, and we must make an extrapolation from the measured point to the actual peak of the H flux. From a separate measurement of the nucleus, we found that the maximum flux at H is only ~5% higher than that measured 0″.5 off center. The structure of the intensity profile, at either r or H, also shows that a 0″.5 misalignment should cause no more than a 0.10 mag error. Thus, we believe the maximum increase allowed in $r - H$ in a 2″.5 diameter aperture between a point 10″ off the nucleus and the nucleus itself is 0.10 mag.

To relate changes in $r - H$ to those in $V - K$, we used correlations of $V - r$ with $V - K$ and $H - K$ with $V - K$ for a sample of early-type galaxies (Zinn and Persson 1980; Persson, Frogel, and Aaronson 1979, respectively). These correlations give $(r - H) = 0.78(V - K) + 0.25$, as one goes from metal-poor to metal-rich galaxies. It is reasonable to assume that any radial gradient in $r - H$ and $V - K$ will have a similar ratio; we then expect a change of not more than $0.10/0.78 = 0.13$ mag in the $V - K$ color within a 2″.5 diameter aperture in going from the nucleus to a point 10″ off the nucleus.

The individual instrumental r- and H-magnitudes measured on the nucleus were calibrated relative to only one standard at r (BD $+17°4708$; $r = 9.50$; Thuan and Gunn 1976) and several at H. The resulting $r - H$ color is 3.1 ± 0.1 mag. By using the same $r - H/V - K$ conversion described above, we obtain a

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1980ApJ...240..779P

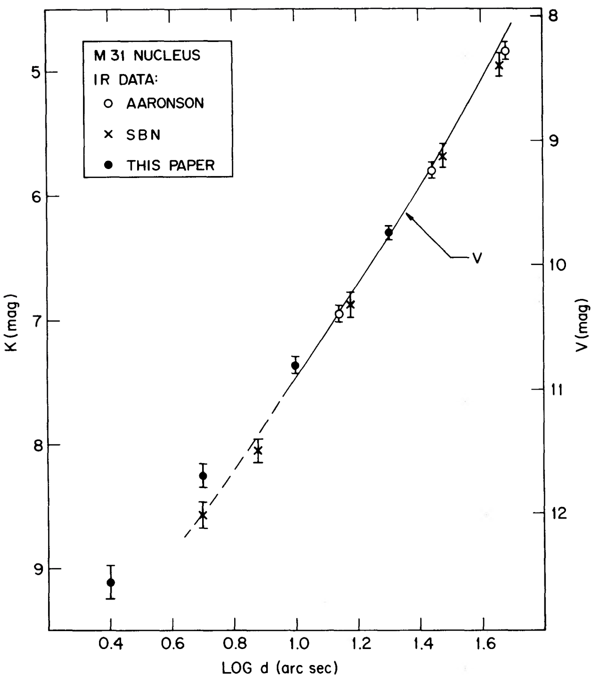

FIG. 2.—The K growth curve near the nucleus of M31, from the data of this paper, Aaronson (1977), and Sandage, Becklin, and Neugebauer (1969; SBN). The smooth curve represents the V data of Kinman (1965), and the V-magnitude scale has been shifted so that $V - K = 3.45$. The reliability of both data sets for apertures smaller than 10″ is questionable, as discussed in the text.

$V - K$ color uncorrected for reddening on the nucleus of 3.6 ± 0.1 mag. This color agrees well with the color exterior to the nucleus of 3.45 ± 0.04 mag (Table 1) together with an increase of no more than 0.13 mag derived above, as one goes to the 2″.5 nucleus itself.

c) *Multiaperture K-Magnitudes*

In the third type of observation, the 2.5 m telescope was used to make a set of multiaperture K measurements of the nucleus in less than 1″ seeing. Data were obtained on 3 nights. Apertures 2″.5, 5″, 10″, and 20″ in diameter were carefully centered on the nucleus, and the reference beam was located 70″ south of the signal beam. The flux entering the reference beam was obtained by direct measurements of the differential flux in steps of 70″ southward off the nucleus until the flux was less than 2% of that on the nucleus. The "sky" location for these data was a field free of stars 10′ north of the nucleus. The flux at this location itself was checked against additional blank fields far from M31; it had a flux less than 1% of that of the nucleus. This direct determination of the reference beam flux was compared with that estimated from the V intensity profile of M31 published by Kinman (1965); the agreement was good. The size of the correction for a 10″ diameter aperture is 0.16 ± 0.02 mag. The apertures were again mapped and convolved with an appropriate intensity distribution to provide "beam profile" corrections. These corrections are less than 0.05 mag. Corrections for flux scattered out of the 2″.5 aperture were also made; these are ~25% compared to a 10″ aperture and dominate the uncertainty for the flux within 2″.5. The causes for such a large correction are not entirely understood but are likely to arise from centering, guiding, scattered light, and seeing problems. An additional uncertainty in the magnitude is due to that of the effective aperture size as defined by an iris diaphragm 0.5 mm in diameter.

The results of the multiaperture 2.2 μm measurements are given in Table 1 and Figure 2. The agreement between different observers is generally good for apertures larger than 10″ in diameter and reasonable for the smaller apertures, considering the difficulty of comparing data taken under different seeing conditions and with different equipment.

In order to derive accurate $V - K$ colors for the nuclear region from these data, it is necessary to compute the V bandpass flux through a matching 2″.5 aperture from published optical surface-brightness measurements. The two sources of data we have considered are the summary and photoelectric recalibration of photographic photometry by Kinman (1965) and the 0″.2 resolution Stratoscope data of Light, Danielson, and Schwarzschild (1974). The V-magnitudes found by integration of these two sources of data, in a 2″.5 diameter aperture, differ by ~0.3 mag. We believe that most of this discrepancy is due to seeing effects. Schweizer (1979) has discussed the effects of seeing on photometry and morphology of galactic nuclei and, using the same M31 data as an example, has shown that spurious values for the nuclear surface brightness can be deduced from data taken in average seeing. Although the seeing disk at 2.2 μm is, on average, only 25% smaller than that at V (Young 1974), the seeing conditions on Mount Wilson at the time our measurements were made were very good (1″ or less). We therefore feel that the uncertainties involved in constructing a $V - K$ color by this method are too great. The best limit we can place on any color gradient close to the nucleus is that found from the $r - H$ measurements, i.e., $V - K$ varies by less than 0.13 mag near the 2″.5 nucleus (see above).

Table 1 also contains the averaged K-magnitudes and $V - K$ colors for apertures larger than 10″. These data show that to within the uncertainties there is no gradient in $V - K$ in a region between 10″ and 100″ in diameter, in agreement with the results of Sandage, Becklin, and Neugebauer (1969).

In column (8) of Table 1 we list the $V - K$ colors corrected for a reddening of $E(V - K) = 0.28$ mag, corresponding to $E(B - V) = 0.10$ mag (van den Bergh 1975).

d) *Summary of Results*

1. There are no systematic changes to within ± 0.01 mag in the CO index and ± 0.02 mag in the H_2O index over the inner 100″ of M31. The lack of variation extends to the 2″.5 diameter "nucleus."

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1980ApJ...240..779P

2. Simultaneous measurements of the r- and H-magnitudes, i.e., a direct determination of the $r - H$ color near the nucleus shows that the maximum change in $r - H$ in a 2".5 diameter aperture between a point 10" off the nucleus and the nucleus itself is 0.10 mag. This corresponds to an increase in $V - K$ of no more than 0.13 mag in going from the bulge to the nucleus.

3. Multiaperture K data near the nucleus were obtained in an attempt to derive accurate $V - K$ colors. The systematic uncertainties, due to seeing effects mostly, in establishing the V flux corresponding to the infrared apertures, make this method unreliable.

III. DISCUSSION

Faber and French (1980) concluded from their study of the Na I λ8190 feature in M31 that within the inner 3" of the nuclear region a drastic change in the stellar population occurs. The model they advocate to fit their data has a strongly dwarf-enriched nucleus $\sim$3" in diameter which is surround by a giant-dominated bulge. The slope of the main-sequence initial mass function in this model changes from $x = 2$ in the nucleus to $x = 0$ in the neighboring bulge (10" away). [In this notation the number of stars per unit mass interval varies as $m^{-(1+x)}$.]

Faber and French (1980) also made quantitative predictions (listed in Table 1) of the behavior of the broad-band $V - K$ color and the narrow-band CO and H_2O indices. The CO index is strong in late-type giants and supergiants and weak or absent in late-type dwarfs of all temperatures, while the H_2O index is strong in very late type giants, supergiants, and dwarfs (Baldwin, Frogel, and Persson 1973; Frogel *et al.* 1978; Persson, Aaronson, and Frogel 1977). The $V - K$ color reflects the effective "temperature" of the composite light; it depends on mean metal abundance, age, and relative giant-to-dwarf ratio.

Of these infrared indicators, only the CO index can unambiguously distinguish between giants and dwarfs. The models of Faber and French (1980) predict a drop in CO index of 0.04 to 0.05 mag in going from the bulge to the nucleus. Note that the FF models give only lower limits to the indices (see Table 1) because of uncertainties in the changes in the strength of the CO and H_2O bands in stars of fixed $T_{\rm eff}$ and surface gravity as the metallicity varies. Thus, although in the FF models the giant branch shifts toward cooler $T_{\rm eff}$ at a fixed luminosity as the metallicity increases, the CO and H_2O indices for any given $T_{\rm eff}$ star were taken as those for solar metallicity. When the metallicity effects on the narrow-band indices are included, the H_2O index, both in individual stars and in the composite model, can only become larger for a metallicity above solar. The CO index will also do so for each star, but since this band is saturated, the increase in the CO index of the composite model cannot be larger than 0.02 mag for any reasonable metallicity increase between the bulge and the nucleus. (These estimates are based on unpublished calculations by J. G. Cohen.) Empirical evidence for a lack of variation of the CO index with metallicity in integrated light comes from the data of Frogel *et al.* (1978) on 51 early-type galaxies. There is no detectable variation ($\pm$0.02 mag) in the CO index over a range of 0.5 in $(V - K)_0$ for the 49 brightest galaxies. If we include NGC 205 and NGC 404, we find $\Delta CO/\Delta(V - K)_0 = 0.07$. Taking our upper limit of 0.13 to the M31 bulge-to-nucleus increase in $(V - K)_0$, we expect no more than a 0.01 mag increase in the CO index due to metallicity alone. The new infrared data on M31 rule out any systematic variation larger than 0.01 mag in the CO index between the largest (107") and smallest (2".5) apertures centered on the nucleus. Therefore, the FF predicted decrease in CO, going from the bulge to the nucleus, *even counteracted by a metallicity increase*, cannot be made consistent with our data in column (2) of Table 1.

The $r - H$ color and the H_2O index *may* show an increase toward the nucleus, and this does agree qualitatively with the FF predictions. However, both these constraints are ambiguous: an increasing proportion of dwarf light is not required, as the very coolest giants also have strong H_2O bands and red $V - K$ colors (see, e.g., Aaronson, Frogel, and Persson 1978). Furthermore, the observed H_2O index in the 2".5 diameter aperture is 0.045 mag *weaker* than the value predicted by FF. This underscores another serious difficulty with the models: the absolute levels of both the $V - K$ color and the narrow-band indices are far too large in the best model for the nuclear color (col. [8] of Table 1).

Although our CO index data argue strongly against a dwarf-enriched M31 nucleus, the present infrared data and the Na I λ8190 data are consistent with a metallicity change of about a factor of 3 between the bulge and the semistellar nucleus as described by Cohen (1979), *provided* that the Na I λ8190 feature in the stars dominating the near-infrared light increases in strength as the metallicity increases. Faber and French (1980) argue that the λ8190 feature is not metallicity sensitive and were thus led to postulate dwarf enhancement in the nucleus as compared to the bulge in order to explain the strong increase in the λ8190 line there. We have not been able to find a satisfactory way out of this discrepancy.

Other explanations, in addition to an overall metallicity enhancement, may be suggested to explain the data on radial gradients in M31. These include changes in the luminosity function of the giant branch, enhancements of Na larger than enhancements of Fe, as suggested by Peterson (1979), and perhaps a non-power-law initial mass function for the red dwarfs which produce the Na feature. Nevertheless, the present data arbue against a large increase in the dwarf/giant ratio, as modeled by Faber and French (1980), as an explanation for the radial changes seen near the nucleus of M31.

This work was supported in part by NSF grant AST 77-20516 and NASA grant NGL 05-002-207.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1980ApJ...240..779P

REFERENCES

Aaronson, M. 1977, Ph.D. thesis, Harvard University.
Aaronson, M., Frogel, J. A., and Persson, S. E. 1978, *Ap. J.*, **220**, 442.
Baldwin, J. R., Frogel, J. A., and Persson, S. E. 1973, *Ap. J.*, **184**, 427.
Cohen, J. G. 1979, *Ap. J.*, **228**, 405.
Faber, S. M., and French, H. 1980, *Ap. J.*, **235**, 405 (FF).
Frogel, J. A., Persson, S. E., Aaronson, M., and Matthews, K. 1978, *Ap. J.*, **220**, 75.
Kinman, T. D. 1965, *Ap. J.*, **142**, 1376.
Light, E. S., Danielson, R. E., and Schwarzchild, M. 1974, *Ap. J.*, **194**, 257.
Persson, S. E., Aaronson, M., and Frogel, J. A. 1977, *A.J.*, **82**, 729.
Persson, S. E., Frogel, J. A., and Aaronson, M. 1979, *Ap. J. Suppl.*, **39**, 61.
Peterson, R. C. 1979, *IAU Symposium 85*, *Star Clusters* (Dordrecht: Reidel), in press.
Sandage, A., Becklin, E. E., and Neugebauer, G. 1969, *Ap. J.*, **157**, 55.
Schweizer, F. 1979, *Ap. J.*, **233**, 23.
Thuan, T. X., and Gunn, J. E. 1976, *Pub. A.S.P.*, **88**, 543.
van den Bergh, S. 1975, in *Stars and Stellar Systems*, Vol. **9**, *Galaxies and the Universe*, ed. A. Sandage, M. Sandage, and J. Kristian (Chicago: University of Chicago Press), p. 509.
Young, A. T. 1974, *Ap. J.*, **189**, 587.
Zinn, R., and Persson, S. E. 1980, in preparation.

J. G. COHEN: California Institute of Technology, 1201 E. California Boulevard, Pasadena, CA 91125

JAY A. FROGEL: Cerro Tololo Inter-American Observatory, P.O. Box 26732, Tucson, AZ 85726

J. MOULD: Kitt Peak National Observatory, P.O. Box 26732, Tucson, AZ 85726

S. E. PERSSON: Mount Wilson and Las Campanas Observatories, 813 Santa Barbara Street, Pasadena, CA 91101

K. SELLGREN: California Institute of Technology, 1201 E. California Boulevard, Pasadena, CA 91125

© American Astronomical Society • Provided by the NASA Astrophysics Data System